HEAT TRANSFER IN EXHAUST SYSTEM OF A COLD START ENGINE AT LOW ENVIRONMENTAL TEMPERATURE

by

Snežana D. PETKOVIĆ[a], Radivoje B. PEŠIĆ[b*], and Jovanka K. LUKIĆ[b]

[a] Faculty of Mechanical Engineering, Banja Luka, Republic of Srpska
[b] Faculty of Mechanical Engineering, Kragujevac, Serbia

Original scientific paper
UDC: 621.43.068.001.573
DOI:

During the engine cold start, there is a significantly increased emission of harmful engine exhaust gases, particularly at very low environmental temperatures. Therefore, reducing of emission during that period is of great importance for the reduction of entire engine emission. This study was conducted to test the activating speed of the catalyst at low environmental temperatures. The research was conducted by use of mathematical model and developed computer programme for calculation of non-stationary heat transfer in engine exhaust system. During the research, some of constructional parameters of exhaust system were adopted and optimized at environmental temperature of 22 °C. The combination of design parameters giving best results at low environmental temperatures was observed. The results showed that the temperature in the environment did not have any significant influence on pre-catalyst light-off time.

Key words: *Exhaust emission, low environmental temperatures, catalyst start, mathematical model*

Introduction

For more than three decades, the catalysts have been used for significant emission reduction. Together with the electronic control of device and system operation in vehicles, the catalysts nowadays reduce the vehicle emission up to 95%. However, the problem is that the catalyst does not function satisfactorily until it reaches the activating temperature, which is 250 °C – 350 °C. Engine operation period until the catalyst and engine reach the starting temperature is called cold start phase. According to references, 60% – 80% of the total CO and HC emission is emitted during this period. At lower environmental temperatures, below 0 °C, this value is 95% – 98% [1, 2, and 3].

Mainly due to poor fuel evaporation in the first few cycles, richer composition (mixture) is required for having safe starting and good driving achievement. This leads to

* Corresponding author, e-mail: pesicr@kg.ac.rs

increase of fuel consumption and emission of incomplete CO and HC combustion products. CO emission is increased due to forming of liquid fuel phase on cooler walls of the intake manifold and cylinder, the so-called "Wall wetting" effect. Depending on the starting temperature and intake system construction, the fuel consumption is increased 5 – 6 times in comparison with the normal working conditions.

Reducing of emission in this period is of particular importance for reducing of the entire vehicle emission. In order to reduce emission during the cold start phase various constructive solutions are applied in both engine and exhaust system.

Two basic approaches are usually, pointed out:

1. Influencing the emission source, and
2. Making impact on faster catalyst action and increase of entire efficiency on additional exhaust gases processing. In references, this approach is very often called "Catalyst Fast Light-off Techniques (FLTs)", [4].

Further distribution of FLTs technique may be done to:

1. Passive system, which means construction alterations on exhaust system, and
2. Active system, which means devices ensuring additional heating required for temperature increase of exhaust gas during engine cold phase.

Passive systems include simple constructional alteration on exhaust pipes and exhaust manifold, which may be used for reducing the heat losses in the atmosphere. Thus, it increases exhaust gas temperature before catalyst and accelerates reaching of its starting temperature. However, in heavy loaded engine operation, attention should be paid on non-overheating the catalyst and occurrence of its faster thermal ageing. When designing an exhaust system, the following parameters should be optimized:

1. Exhaust pipes – number of pipes, insulated or not, having one or double walls or double and air-gap, selection of exhaust pipe materials, selection of pipe geometric parameters (length of individual parts, wall thickness, number of pipe curves and their radii, selection of insulation pipe and its thickness), and
2. Catalyst – selection of catalyst location, number of catalyst bricks, relation between the length and radius, cell density, material density and bearing coat thickness (Wash Coat) and active layer.

The listed FLTs systems provide good results in emission reducing, however, it is necessary to determined which system or their combination is the best for the appropriate vehicle – engine – exhaust system – catalyst.

Regarding the huge number of constructional parameters of the exhaust system, it is almost impossible to perform optimization without use of mathematical models and computers (CAE – Computer Aided Engineering), which significantly decrease design period and make the product cheaper [5]. Therefore, a mathematical model was designed to simulate heat and mass transfer processes in the engine pipes and the catalyst [6, 7]. Since there are various processes that take place in the catalyst and engine exhaust pipes, two models have been developed.

One model is developed to simulate heat transfer processes in engine exhaust pipes aimed at determining of such constructional solution of exhaust pipes (geometry, pipes number, insulation, *etc.*) to achieve the least temperature loss of the exhaust gas before the catalyst and thus accelerate its start.

The other model is developed to simulate heat and mass transfer processes in the catalyst. The exit parameters from the exhaust pipes model are the catalyst input parameters. If there are some additional systems for the catalyst accelerated start on the exhaust system, such as: electrically heated catalyst, absorber or secondary air input system, then it is possible to develop a special mathematical model for them, too.

Since the catalyst is not active, it should be mentioned that, during the engine cold start, chemical reactions speed is very low so they are neglected as well as the heat originating from exothermal reactions. It is taken that the catalyst functions as a converter.

Heat transfer by radiation is significant only at high temperatures, in monolith if its temperature exceeds 1000 K, and in exhaust pipes and from the catalyst coating if their temperature exceeds 700 K, [7].

The main goals of the paper are to summarize our own research and to obtain preliminary results which may be used in the design and making of the experimental device for verification of the mathematical model.

Mathematical model of heat propagation in the engine exhaust system

Figure 1 shows the main parts of the engine exhaust system and models that are used for some parts.

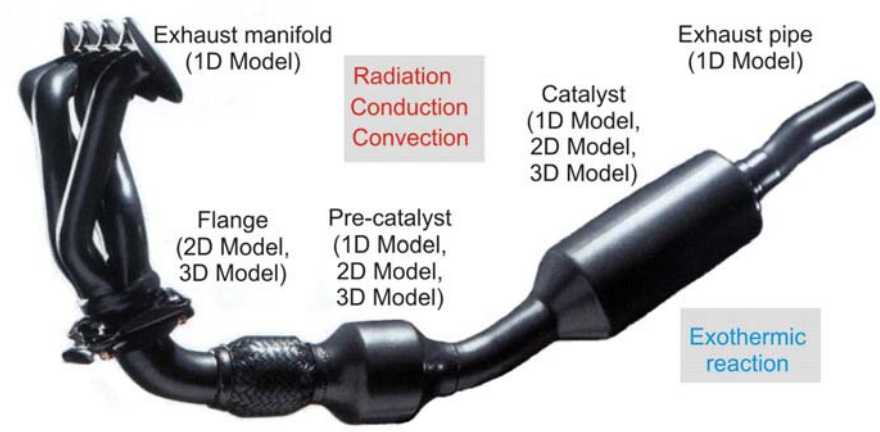


Figure 1. The appearance of the engine exhaust system
(1D – one-dimensional, 2D – two-dimensional, 3D – three-dimensional models)

An unsteady turbulent flow of compressible fluids is present in the engine exhaust pipes. When the exhaust gas flow through the engine exhaust pipe heat transfer takes place through forced convection. In addition to convection, this model takes into account the axial conduction along the pipe, natural or forced convection, and radiation from the external pipe to the environment. In the modeling process of heat transfer to the wall of exhaust pipes should be more to know: whether the pipe with one wall, is insulated pipe, is the double wall

pipe and an air-gap between them, as well as constructional characteristics (diameter and wall thickness of pipes, the number of curves of pipe and their curvature radius) and pipes and insulation material (density, coefficient of thermal conductivity and specific heat).

During the process of heat transfer in exhaust pipes at the same time there are the changes in gas and wall temperature along the pipe length and with the time (non-stationary change). To define a mathematical model of the unsteady change of gas temperature and wall temperature two approaches are used:

– One approach is to take a uniform heat flux from gas to wall (or wall on the gas) at a very rapid change and
– The second approach is to take a uniform wall temperature (T_m = const. – Isothermal wall), at the slow change.

The second approach can be used for this model. Process modeling of heat transfer in the exhaust pipe is thoroughly studied within the paper [6]. Here we keep the detail on the model of catalysts.

Description of the model catalyst

Monolith channel with not cylindrical shape is simulated like a cylindrical shape channel with equivalent input cross-section and length. Figure 2 shows a control volume of the monolith channel.

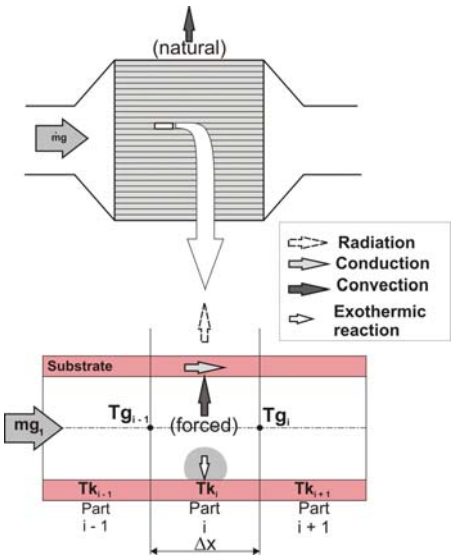


Figure 2. Control volume of monolith channel

When designing a model of heat transfer in the catalyst during the cold start engine the following were taken into account:

1. Convectional heat transfer from gas to the catalyst channel;
2. Heat that originates from exothermal reactions of particular components of exhaust gases is neglected since the catalyst is not active. The catalyst is considered to function as a converter;
3. Heat transfer by radiation is significant only when temperatures are higher, from the monolith to the catalyst coating if its temperature is higher than 1000 K, and in exhaust pipes and from the catalyst coating if their temperature is higher than 700 K;
4. The loss of heat by convection (either natural or forced) and due to radiation from the catalyst coating on the environment (substantial at higher temperatures);
5. Uniform distribution of gas temperature and velocity at the catalyst input;
6. Laminar gas flow in the monolith channel;
7. Conduction and radiation are inconsiderable in gas phase in comparison to convection;

8. Gas properties are changing depending on gas temperature and pressure, whereas the catalyst material properties do not change significantly due to its temperature change,;
9. Temperature and concentration of gas is identical for all catalyst channels, and
10. Within a short time step which is taken in calculations in one small part of monolith catalyst channel (control volume) quasi-stationary assumptions can be applied, *i. e.* stationary change of temperature and gas concentration can be considered whereas non-stationary flow can be neglected therefore derivations by time can be neglected. Within the adopted time calculation step it can be stated that the temperature of the catalyst body does not change, which is realistic due to typical temperature inertia of the catalyst material.

Based on the aforementioned assumptions, calculation procedure for each time step is done in the following way:

1. Calculating temperature of the gas phase along the length of the appropriate channel, and
2. Calculating temperature of the catalyst body.

Gas phase

In the Cartesian coordinate system for one-dimensional problems of energy conservation equation is given by eq. (1):

$$\varepsilon \frac{\partial T_{\mathrm{g}}}{\partial t} + u \frac{\partial T_{\mathrm{g}}}{\partial x} = \frac{-\delta \dot{Q}_{\mathrm{cvu}}}{\rho_{\mathrm{g}} V_{\mathrm{uk}} c_{\mathrm{pg}}} = -\frac{\alpha_{\mathrm{cvu}} S_{\mathrm{l}} \left(T_{\mathrm{g}} - T_{\mathrm{k}}\right)}{\rho_{\mathrm{g}} V_{\mathrm{uk}} c_{\mathrm{pg}}} \,. \tag{1}$$

If $\frac{\partial T_{\mathrm{g}}}{\partial t} = 0$ is taken, then follows:

$$u \frac{\partial T_{\mathrm{g}}}{\partial x} = -\frac{\alpha_{\mathrm{cvu}} S \left(T_{\mathrm{g}} - T_{\mathrm{k}}\right)}{\rho_{\mathrm{g}} c_{\mathrm{pg}}} \,, \tag{2}$$

where:

α_{cvu} – is heat transfer coefficient from gas to the catalyst channel, [W·m^{-2}·K^{-1}],
T_{g} – is gas temperature in the catalyst channel, [K],
T_{k} – is temperature of the catalyst surface, [K],
ρ_{g} – is mass density of the gas, [kg/m^3],
c_{pg} – is specific heat of the gas at constant pressure, [J·kg^{-1}·K^{-1}],
S – is geometric surface of the catalyst as per volume unit, (= $S_{\mathrm{l}}/V_{\mathrm{uk}}$), [m^2/m^3],
t – is time (=$n\cdot\Delta t$, $n=0,1,2,3...N$), [s],
Δt – is time step, [s],
u – is velocity of fluid flow, [m/s],
x – is axial distance from the pipe inlet (=$i\cdot\Delta x$, $i=0,1,2,3...M$), current coordinates, [m],
Δx – is grid space distance, [m],
ε – is catalyst porosity [–], and

$\dot{Q}_{\mathrm{cvu}}$ – is heat flux from gas to the catalyst material, ($= dQ_{\mathrm{cvu}} / dt$), [J/s].

The Catalyst Material

Since exothermal reactions in the catalyst are neglected during the cold start, mere equations of energy conservation are sufficient for calculation (it is not needed to consider mass transfer equations), eq. (3):

$$(1-\varepsilon)\rho_{\mathrm{k}}\, c_{\mathrm{k}} \frac{\partial T_{\mathrm{k}}}{\partial t} = (1-\varepsilon)\lambda_{\mathrm{k}}\left(\frac{\partial^2 T_{\mathrm{k}}}{\partial x^2}\right) + \frac{\dot{Q}}{V_{\mathrm{uk}}} \,. \tag{3}$$

Heat flux, ($\dot{Q}$) includes: heat transfer rate by convection from gas to the catalyst ($\dot{Q}_{\mathrm{cvu}}$), heat transfer rate by electric heating of the catalyst, heat transfer rate by convection onto the environment ($\dot{Q}_{\mathrm{cvo}}$). As it was mentioned before, the heat that is a result of exothermal reactions and the heat transfer rate by radiation to the catalyst coating and from the coating to the environment is neglected:

$$\begin{aligned} \dot{Q} &= \dot{Q}_{\mathrm{cvu}} - \dot{Q}_{\mathrm{cvo}} \,, \\ \dot{Q} &= \alpha_{\mathrm{cvu}} S_{\mathrm{l}} (T_{\mathrm{g}} - T_{\mathrm{k}}) - \alpha_{\mathrm{cvo}} S_{\mathrm{lo}} (T_{\mathrm{k}} - T_{\mathrm{o}}) \,, \end{aligned} \tag{4}$$

where:

ρ_{k} – is mass density of the catalyst, [kg/m^3],
c_{k} – is specific heat of the catalyst, [J·kg^{-1}·K^{-1}],
λ_{k} – is thermal conductivity of the catalyst, [W·m^{-1}·K^{-1}],
α_{cvo} – is heat transfer coefficient from the catalyst onto the environment, [W·m^{-2}·K^{-1}], and
S_{lo} – is outer surface of the catalyst, [m^2].

Differential equations solutions

Differential equations of heat transfer are solved using the finite difference method.

The change of temperature and concentration of gas in the catalyst during a period of time are taken as a series of quasi-stationary states.

Initial conditions were:

$$t=0, \quad 0 \le x \le L = M \cdot \Delta x, \quad T_{\mathrm{k}}(x,0) = T_{\mathrm{kp}} \,. \tag{5}$$

Boundary conditions were:

$$x=0, \quad 0 \le t \le N \cdot \Delta t, \quad T_{\mathrm{g}}(0,t) = T_{\mathrm{g,ul}} \tag{6}$$

Since the conduction of heat through monolith is considerably higher than convection on the front and rear monolith surface, the heat flux is neglected on these two surfaces, *i. e.*:

$$\frac{\partial T_{\mathrm{k}}}{\partial x}\Big|_{x=0} = 0 \quad \Rightarrow \quad T_{\mathrm{k},0}{}^{n} = T_{\mathrm{k},1}{}^{n}, \tag{7}$$

$$\frac{\partial T_{\mathrm{k}}}{\partial x}\Big|_{x=L} = 0 \quad \Rightarrow \quad T_{\mathrm{k},i}{}^{n} = T_{\mathrm{k},i+1}{}^{n}, \quad i = M, \tag{8}$$

With the known initial condition, eq. (5), the catalyst temperature in the first iteration step is known, then T_g is calculated from the eq. for energy conservation (2), together with the boundary condition (6), using local analytical solution (similar to the pipes):

$$T_{\mathrm{g},i}{}^{n} = T_{\mathrm{k},i}{}^{n} + (T_{\mathrm{g},i-1}{}^{n} - T_{\mathrm{k},i}{}^{n})e^{-NTU}, \tag{9}$$

$$NTU = \frac{\alpha_{\mathrm{cvu}} \Delta F}{\dot{m}_{\mathrm{g}} c_{\mathrm{pg}}}, \tag{10}$$

where:

ΔF – is surface of the catalyst segment through which heat is exchanged [m^2].

From eq. (3) under boundary and initial conditions given by *eqs.* (5), (7), and (8) temperature of the catalyst surface T_k is calculated in a point of time and along the channel length by application of the finite difference method. Approximation of time derivative by finite differences is done by applying backward difference, whereas the approximation of second derivatives by space is done by using central difference [7].

Discretized form of eq. (3), combining the eq. (4), is as follows:

$$T_{\mathrm{k},i}^{n} = T_{\mathrm{k},i}^{n-1} + a_{\mathrm{k},i}{}^{n-1} \frac{\Delta t}{\Delta x^2}(T_{\mathrm{k},i+1}^{n-1} - 2T_{\mathrm{k},i}^{n-1} + T_{\mathrm{k},i-1}^{n-1}) + \frac{\delta \dot{Q}_{\mathrm{cvu}} - \delta \dot{Q}_{\mathrm{cvo}}}{\rho_{\mathrm{k}} c_{\mathrm{k}} (1-\varepsilon) V_{\mathrm{uk}}} \Delta t \Big|_{i}^{n-1}. \tag{11}$$

Stability criteria are taken to be the same as in the pipe models [6, 7].

For hyperbolic equations:

$$C = u \frac{\Delta t}{\Delta x} \leq 1. \tag{12}$$

For parabolic equations:

$$d = a_k \frac{\Delta t}{(\Delta x)^2} \leq \frac{1}{2}, \tag{13}$$

where:

C – is *Courant* number, [–],
Δt – is time step, [s],
Δx – is grid space distance, [m],
d – is diffusion number, [–], and
a_{k} – is thermal diffusivity of the catalyst, ($=\lambda_{\kappa} / \rho_{\mathrm{k}} / c_{\mathrm{k}}$), [$m^2 \cdot s^{-1}$].

Based on the defined mathematical model for engine exhaust pipes and the catalyst, "TERMO" computer programme was developed for calculation of non-stationary heat transfer in the engine exhaust system [7]. The programme was designed in BASIC computer language. The programme calculates temperatures of gases and pipes wall, *i. e.* catalyst in the exhaust system that may contain 10 different modules.

Gas temperature at the exhaust system input (limit condition) is supposed to be given constant or second-degree polynomials. Optionally, the programme may take (process) the measured gas temperature values at engine exit or the values obtained by calculation, using the appropriate programme for engine operating cycle calculation.

Since the calculation for the catalyst and the pipes differs, the programme contains the option to decide interactively, for each calculated part, whether it is about the pipe or the catalyst. Based on made choice, the sub-programme is automatically started for the appropriate calculation (the pipe or the catalyst). The programme also contains the possibility for taking into consideration radiation during the calculation process or its negligence.

During the calculating process, the monitor may show a graph with changes of both gas temperatures and wall pipe temperatures, and immediately follow the calculation correctness. Upon completion of calculation, the programme creates database outputs for calculation results of the selected part of the system. For some other part, the programme should be reactivated. The obtained output databases are gas temperatures in the selected part (Tgas.dat), material temperatures (Tmat.dat) in the selected part, mean temperature of the material part (Tmid.dat) and the input data and heat balance database (pod.dat). If it is about the double wall and insulated pipe, databases regarding temperature change of the external pipe (Tmout.dat) and insulation (Tins.dat) are also obtained. Figure 3 shows "TERMO" programme block diagram.

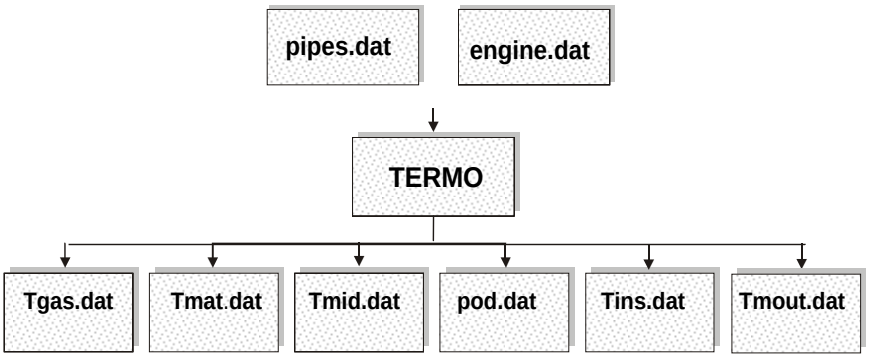


Figure 3. "TERMO" programme block diagram

The developed model and the programme have been further used for testing of great number of pipes and catalyst parameters on the catalyst start as well as the testing on low environmental temperatures. Low environmental temperatures testing was so conducted that the catalyst and exhaust pipes parameters were optimized at the environmental temperature of 22 °C and then testing of this system was performed at low environmental temperatures.

Table 1. Characteristics of the exhaust system elements

No	Exhaust system element	L [mm]	D [mm]	δ [mm]	Mater.	ρ_m [kg/m^3]	λ_m [W·m^{-1}·K^{-1}]	c_m [J·kg^{-1}·K^{-1}]
1	Exhaust pipe with 2 mm air-gap	200	39	1.5	Č.4571	7900	15	477
2	Metal pre-catalyst, ε = 0.9, and 400 cps,	75	70	1.2	Č.4571	7900	15	477
3	Exhaust pipe with 2 mm air-gap, lower than the pre-catalyst	500	39	1.5	Č.4571	7900	15	477
4	Basic catalyst with ceramic monolith, ε = 0.9, and 400 cps,	140	100	–		1800	1.5	1020
	Catalyst insulation			3	glass wool	200	0.03	660
	Catalyst external panel			1.2	Č.4571	7900	15	477
5	Exhaust pipe	200	39	1.5	Č.4571	7900	15	477

Figure 4 shows a scheme of a tested exhaust system with all the elements, and the tab. 1 shows optimized construction characteristics of the exhaust system.

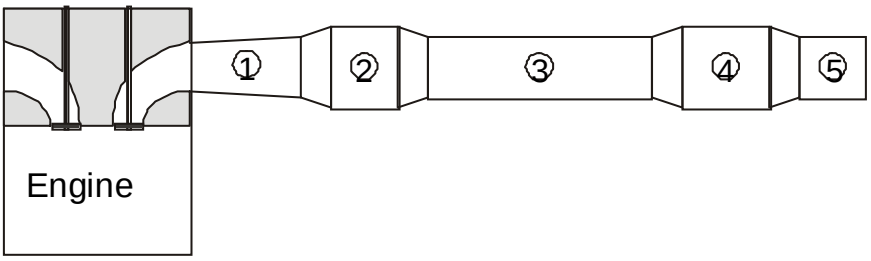


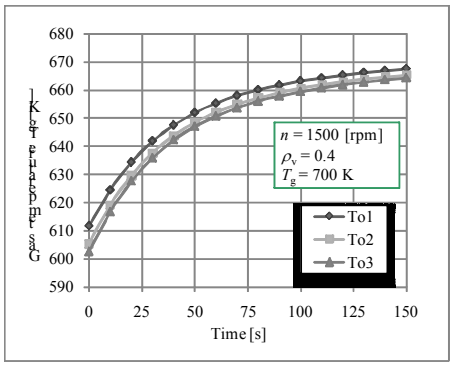
Figure 4. Exhaust engine system scheme (see legend in the tab. 1.)

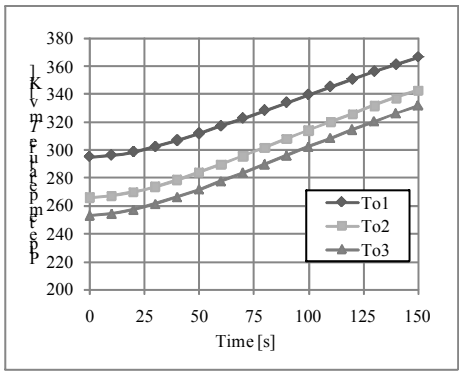
Influence of environmental temperature

In order to test the influence of low environmental temperatures on thermal behavior of the exhaust system, testing was conducted on environmental temperatures: T_{o2} = –7 °C and T_{o3} = –20 °C. For each testing, gas temperature at the exhaust system input was adopted and it was T_g =700 K, volumetric efficiency η_v = 0.4 and engine speed was 1500 rpm.

Figure 5 shows gas temperature change at the pipe exit, *i. e.* at the pre-catalyst

input. The figure shows that with the environmental temperature lowering, gas temperature at the pipe exit falls but not significantly. Figure 6 shows the change of external pipe temperature. Although the differences in external pipe temperatures are more obvious, they still have neither significant influence on the heat emitted in the environment nor on total heat balance which had effect on a slight change of gas temperature.

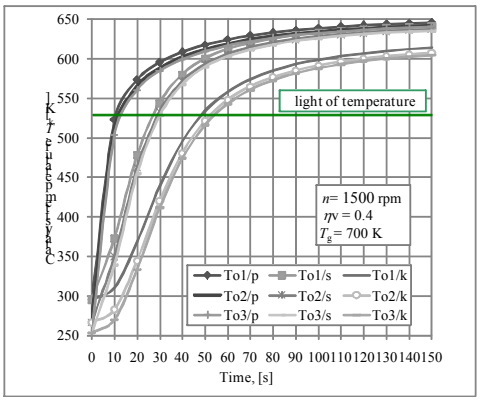


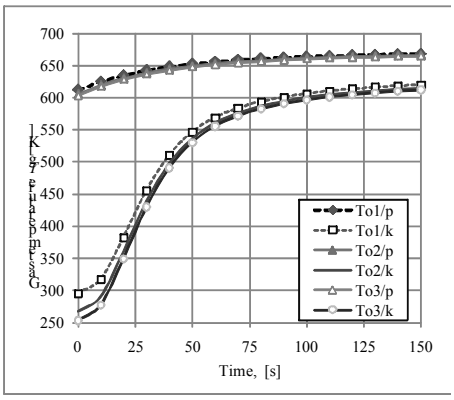


(environmental temperature: T_{o1}= +22 °C, T_{o2} = –7 °C, T_{o3} = –20 °C)

Figure 5. Change in gas temperature at the pipe no 1 exit (at the pre-catalyst input)

Figure 6. Change in external pipe temperature in pipes 1 before the pre-catalyst





(p – beginning, s – middle, k – end of the catalyst,)
(environmental temperature: T_{o1}= +22 °C, T_{o2} = –7 °C, T_{o3} = –20 °C)

Figure 7. Change in pre-catalyst temperature

Figure 8. Change in pre-catalyst gas temperature

Figure 7 shows the change in pre-catalyst temperature, and figure 8 shows the change in pre-catalyst gas temperature. Figures show that there is no big difference in pre-catalyst gas temperatures. The pre-catalyst has slower start at lower environmental temperatures (about 3 s – 5 s slower). There is no significant difference in pre-catalyst temperatures at temperatures below 0 °C.

Change in environmental temperature has more influence on the basic catalyst start. Figure 9 shows change in catalyst temperature. It is evident that at environmental temperature of +22 °C, the catalyst has faster start in its first part for 25 s in comparison with the environmental temperature of –7 °C. Figure 10 shows change in catalyst gas temperature at specific locations. Catalyst temperature follows gas temperature.

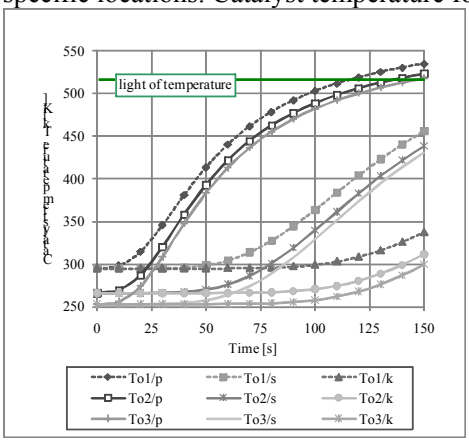


Figure 9. Change in basic catalyst temperature

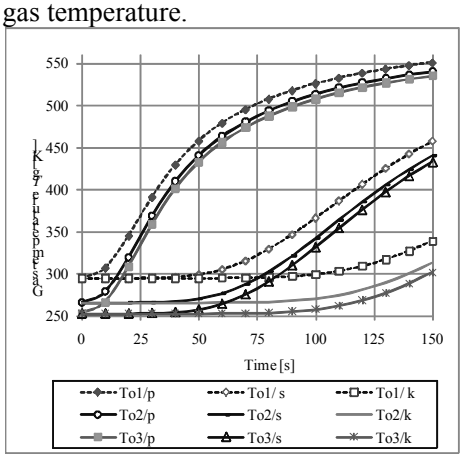


Figure 10. Change in basic catalyst gas temperature

*(*p – *beginning,* s – *middle,* k – *end of the catalyst,)*
(environmental temperature: T_{o1} *= +22* °C, T_{o2} *= –7* °C, T_{o3} *= –20* °C*)*

Conclusions

According to the conducted testing, the following may be concluded:

Environmental temperature has no significant influence on pre-catalyst start speed. The outer surface through which heat is emitted into atmosphere is small, so regardless of the change in the external pipe temperature, there is no significant change in the quantity of heat emitted into atmosphere. It may be considered that the heat flux between exhaust gas and the catalyst is almost the same at low and normal environmental temperatures. Pre-catalyst insulation has also no significance on its start speed. Pre-catalyst insulation is only significant at higher loading in order to protect the neighboring parts of vehicle equipment from overheating and air-gap insulation should be selected.

A significantly greater influence of environmental temperature on catalyst activating speed has been noticed in basic catalyst, because the outer surface through which heat is emitted into atmosphere is larger, hence the heat capacity of the parts before the catalyst is also greater.

Nomenclature

a_k – Thermal diffusivity of the catalyst, $(=\lambda_\kappa/\rho_k/c_k)$, [$m^2 \cdot s^{-1}$]

C – *Courant* number, $(=u\frac{\Delta t}{\Delta x}\le 1)$, [–]
c – specific heat, [J·kg^{-1}·K^{-1}]
c_{pg} – specific heat of the gas at constant pressure, [J·kg^{-1}·K^{-1}]
D – diameter of pipe, [m]
d – diffusion number, [–]
L – length of pipe, [m]
M – number of time segments, [–]
N – number of length segments, [–]
$\dot{Q}$ – heat flux, [J/s]
S – geometric surface of the catalyst as per catalyst volume unit (= S_l/V_{uk}), [m^2/m^3]
S_l – inner surface of the catalyst, [m^2]
S_{lo} – outer surface of the catalyst, [m^2]
t – time, [s]
T – temperature, [K]
V_{uk} – volume of catalyst, [m^2]
u – velocity of fluid flow, [m/s]

Greek letters

α – heat transfer coefficient, [W·m^{-2}·K^{-1}]
ΔF – surface of the catalyst segment through which heat is exchanged, [m^2]
Δt – time step, [s]
Δx – grid space distance, [m]
λ – thermal conductivity, [W·m^{-1}·K^{-1}]
η_v – volumetric efficiency [–]
ρ – density, [kg/m^3]
ε – catalyst porosity, [–]

Subscript

cvu – from gas to the catalyst channel
cvo – from the catalyst onto the environment
g – gas
k – catalyst
k – end
m – material
o1 – environmental 1
o2 – environmental 2
o3 – environmental 3
p – beginning
pg – gas at constant pressure
s – middle

References

[1] Laurikko, J., Exhaust Emissions Performance of In-Use TWC Cars at Low Ambient Temperatures, *Proceedings on CD*, 25th World Automotive Congress FISITA 1998, Paris, France, 1998, pp. F98P090
[2] Petrović, S., Kuzmanović M., Popović V., The Control of passengers' cars exhausts emissions: *Mobility &Vehicle Mechanics, Vol 20*, (1994), pp. 8 – 15
[3] Marsh, P., *et al*., Application Guideline to Define a Catalyst Layout for Maximum Catalytic Efficiency, *SAE Paper 2001 – 01 – 0929*, (2001)
[4] Petković, S., Mrđa, J., Catalyst Fast Light-Off Techniques for SI Engines (on Serbian language), *Proceedings*, International Scientific Symposium IPS 2001", Podgorica – Becici, SR Yugoslavia, 2001, pp. 151 – 160
[5] Konstantinidis, A. P., Kolltsakis, C. G., Stamatelos, M. A., The Role of Computer Aided Engineering in the Design Optimization of Exhaust After-Treatment Systems, *Journal of automobile engineering, Proceedings Part D, 212*, (1998), 3, pp. 169 – 186
[6] Petković, S., *et al.,* Heat Transfer Modelling in the Exhaust Pipes of Engine, *Proceedings*, 12th International scientific symposium Motor Vehicle and Engines, Kragujevac, Serbia, 2002, pp. 201 – 204
[7] Petković, S., Exhaust System of Engine Optimization at Low Temperature Working Regime (on Serbian language), *Ph. D. Thesis*, Faculty of mechanical engineering, Banja Luka, BiH, 2002
[8] Petković, S., Mrđa, J., Milašinović, A., Influence of Exhaust System Construction Parameters on Thermal Response of Catalyst (on Serbian language), *Proceedings on CD*, International scientific symposium IPS 2003, Podgorica –Bečići, SR Yugoslavia, 2003

Paper submitted: May 05, 2010
Paper revised: May 31, 2010
Paper accepted: July 31, 2010